Journal of the Faculty of Environmental Science and Technology, Okayama University
Vol.3, No.1, pp.127-134, January 1998

Effect of Matric Suction on Shear Characteristics of Unsaturated Fraser River Sand

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(Received October 31, 1997)

ABSTRACT

This paper discusses the shear strength and volume change characteristics of a loose Fraser River sand. Suction-controlled simple shear tests were carried out for the unsaturated sand. Drained tests for the saturated sand were also carried out for the comparison with the unsaturated sand.

The increase of the shear strength of the sand with the matric suction is very small and there is almost no increase of that over 20 kPa of the matric suction. The suppression effect of the matric suction on the volume change behavior during shear is small, and the degree of dilation increases with the increase of the matric suction.

Key Words : *unsaturated sand, shear strength, simple shear test, matric suction, volume change, dilatancy*

1. INTRODUCTION

Water held among soil particles forms capillary menisci in an unsaturated soil. The curved air-water interface produces the negative pressure in the pore water and then generates interparticle attractive forces among the soil particles. Fisher (1926) has shown a formula giving the interparticle force at the contact point of two equal-sized spheres. Shimada et al. (1993) have presented an equation of the increase of the normal stress on the shear plane due to the interparticle force in a randomly packed assembly of equal-sized spheres. The increase of the normal stress can affect shear characteristics of soils. The effect of the negative pore water pressure on shear properties of unsaturated sands has not been studied well because the magnitude of the interparticle force depends on the particle size and it is believed that the force in sands is small and has not great effects on the shear behavior.

This paper discusses the effects of the negative pore water pressure on the shear strength and volume change characteristics of an unsaturated sand.

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2. MATERIAL AND TESTING PROCEDURE

The soil used for this experiment is a clean uniform sand taken from Fraser River in Delta, British Columbia, Canada. It is well known as the Fraser River sand. The sand was thoroughly washed with the sieves whose openings were 1mm and 0.1 mm. **Fig. 1** shows the particle size distribution curve (Sivathayalan, 1997). The sand is poorly-graded and its uniformity coefficient (U_c) is 1.5.

All tests were carried out with NGI type simple shear apparatus (Bjerrum & Landva, 1966), which uses the wire reinforced membrane for an encasement of a specimen.

The specimens were prepared with the water pluviation technique (Vaid & Negussey 1984, Kuerbis & Vaid 1988). The technique produces uniform samples of poorly-graded sands, such as the Fraser River sand, without the problem of particle segregation. The sand was saturated by boiling, and placed under water into the reinforced membrane supported by the split forming mould. The diameter of the specimens was 70 mm and their initial heights were about 16 mm.

After the application of the normal stress, the negative pressure was applied to the specimen through a ceramic disc embedded in the lower pedestal, and was kept constant during shear. The disc has the air entry value higher than 100 kPa. Even though the sand has high permeability, it takes much time to drain the water from the specimen because of low permeability of the ceramic disc. **Fig. 2** shows the typical drainage curves with the different negative pore water pressures applied to the specimens. When we employ the water pluviation technique for ensuring the uniformity and the saturation of the specimens, this time-consuming drainage process is inevitable.

The shearing phase was stress-controlled with a Basic program by a personal computer. After the velocity of the horizontal displacement in each loading step became smaller than 0.002 mm/min, the next shear stress increment was applied to the specimen. When the horizontal displacement exceeded 4 mm, where the shear strain was about 25 %, no further increment of the shear stress was applied and the horizontal shear stress at this point was defined as the shear strength in this paper.

The matric suction (S_u) is defined as follows :

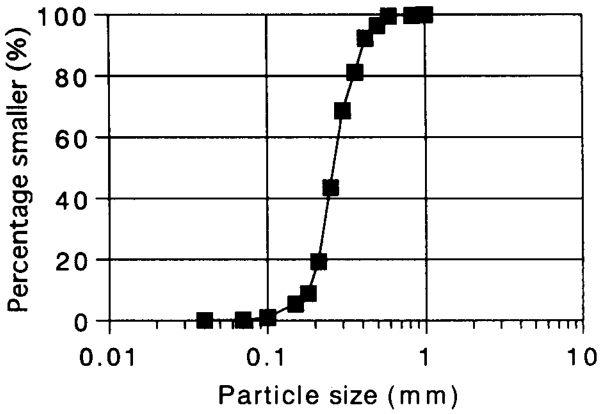

Fig. 1 Particle size distribution curve of Fraser River sand

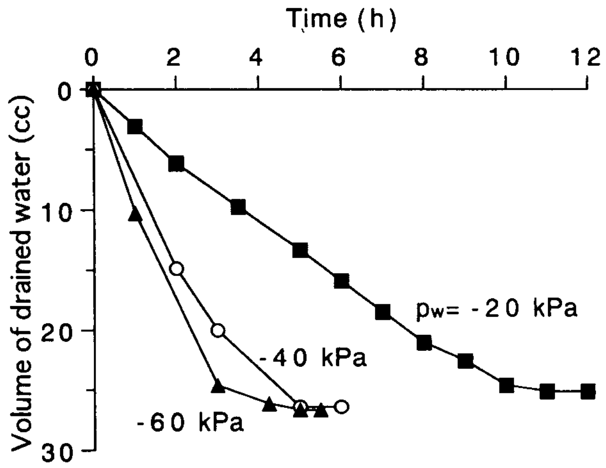

Fig. 2 Drainage under different negative pore water pressure (pw)

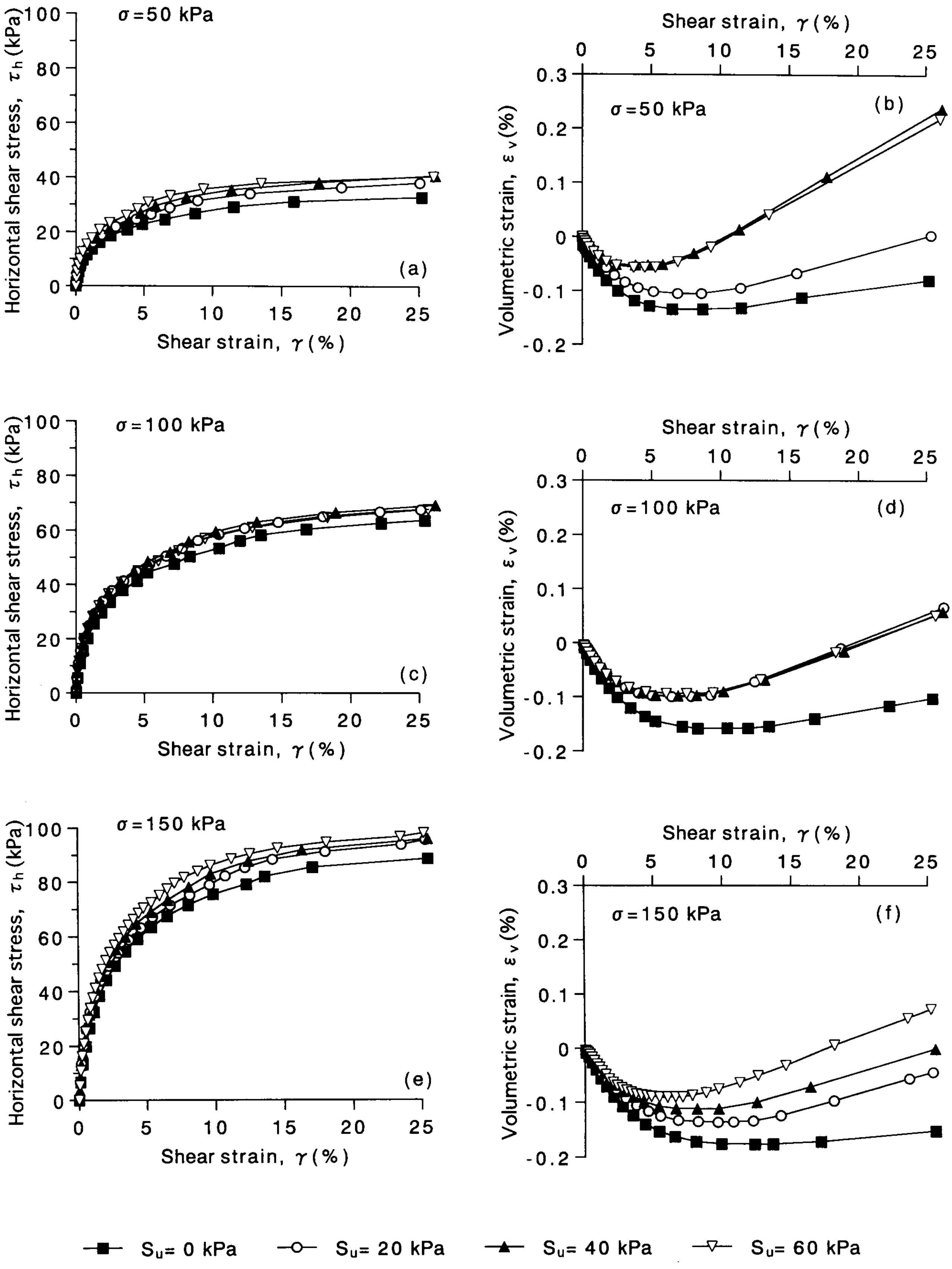

Fig. 3 γ- τ_h- ε_v relationships of Fraser River sand for different normal stress (σ) and matric suction (Su)

$$S_u = u_a - u_w, \qquad (1)$$

where u_a is the pore air pressure and u_w pore water pressure. The upper drainage line connected to a specimen was kept open during shear, then u_a was equal to atmospheric pressure and $-u_w$ the matric suction. The matric suctions, S_u = 20, 40, 60 kPa were applied in this series of the tests.

The conventional drained tests for saturated specimens were also carried out for the comparison with results of unsaturated specimens. This test is called S_u = 0 tests in this paper.

3. RESULTS AND DISCUSSION

Fig. 3 shows the typical test results under different normal stress (σ) conditions; figures (a)(c)(e) the relationships between the shear strain (γ) and the horizontal shear stress (τ_h); figures (b)(d)(f) the relationships between the shear strain (γ) and the volumetric strain (ε_v). ε_v is positive for the volume increase.

The magnitude of the normal stresses and the matric suctions applied to the specimens are denoted in the figure.

3.1 Strength characteristics

Fig. 4 summaries all test results with the relationships between the matric suction (S_u) and the shear strength (τ_f). The shear strengths of unsaturated specimens are greater than those of saturated one. Bilinear lines are intentionally drawn for each relationship under the different normal stress (σ). The symbols representing the test results fairly fit to the bilinear relations. The increase of τ_f is negligibly small in the region of S_u values greater than 20 kPa.

Fig. 5 shows the experimental results of suction-controlled direct shear tests carried out by Escario & Sáez (1986) for Madrid clayey sand. The sand shows also the bilinear relations between the matric suction and the shear stress.

As theoretically predicted (Shimada et al., 1993), the increase of the normal stress for a relatively large particle size soil is small and the matric suction has the small influence on the shear strength.

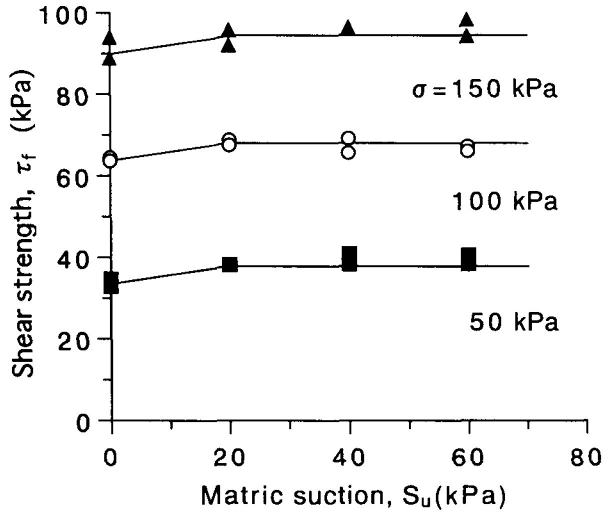

Fig. 4 Change of shear strength of Fraser River sand with matric suction

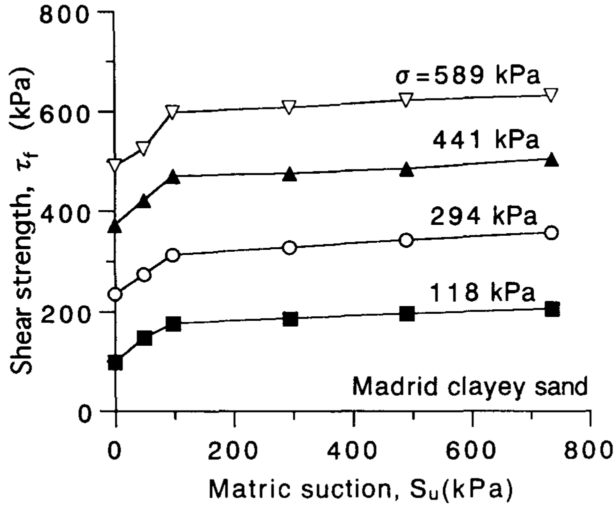

Fig. 5 Change of shear strength of Madrid clayey sand with matric suction (from Escario & Sáez, 1986)

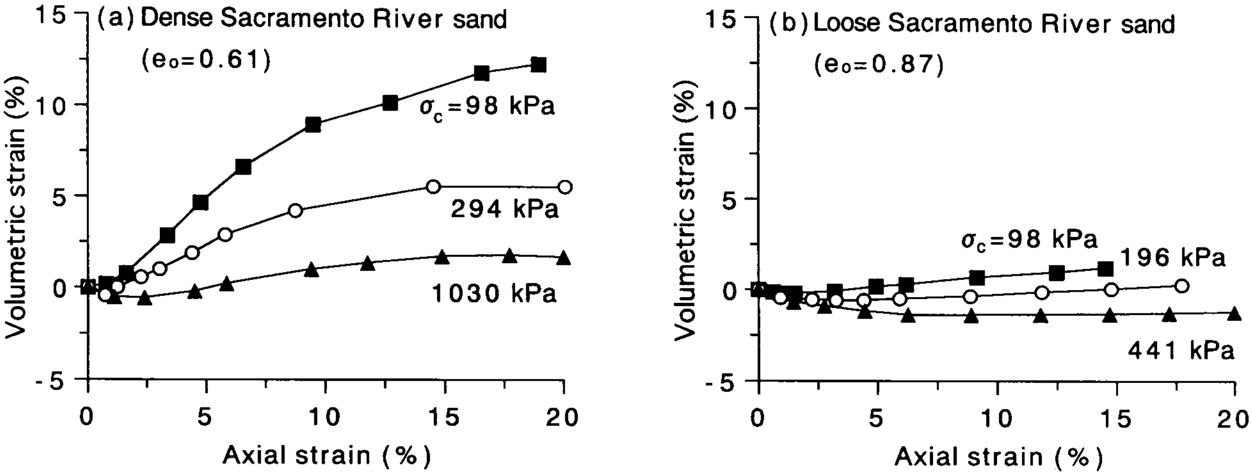

Fig. 6 Dilatancy characteristics of saturated loose and dense Sacramento River sand (Lee & Seed, 1967)

3.2 Volume change characteristics during shear

The characteristics of the volume change of sands during shear depend strongly on the confining pressure and the initial void ratio. **Fig. 6** shows the results of drained triaxial compression tests for a saturated dense and loose sand (Lee & Seed 1967), comparing the dilation characteristics, *i.e.*, the relationships between the shear strain (γ) and the volumetric strain (ε_v). The following is evident from the figure:

- ♦ The dense specimen shows higher dilation than the loose specimen under the same confining pressure (σ_c).
- ♦ Under the same initial void ratio (e_o), the confining pressure suppresses the degree of dilation.

The application of the consolidation pressure has two kinds of effects on the behavior of sand specimens:

1) decrease of the void ratio due to consolidation,
2) increase of the effective confining pressure, which suppresses the deformation of specimens during shear.

According to the first evidence from **Fig. 6**, the decrease of the void ratio produces the tendency of higher dilation. Then, the specimen of the same initial void ratio can be expected to show higher dilation under the higher confining pressure. However, the effect of the suppression of the confining pressure must be dominant under the same initial void ratio, then actually, the specimens less dilate under the higher confining pressure. We can then conclude that the dilatancy characteristics depend on the balance of the intensity of the two effects previously mentioned.

Fig. 7 summaries the results of S_u = 0 tests in **Fig. 3**, *i.e.*, the dilatancy characteristics of the saturated specimens. The tendency of dilation of the Fraser River sand is the same as that of the Sacramento River sand shown in **Fig. 6**, *i.e.*, the higher confining pressure suppresses the degree of dilation of the saturated specimens of the same initial void ratio.

We then consider the dilation behavior of the unsaturated specimens.

The components of S_u are pore air and pore water pressure, u_a and u_w, respectively in Eq. (1). These pressures are isotropic. Then, it can be expected that the application of S_u has also the same effects as that of the consolidation pressure, 1) and 2) listed previously, on the volume change behavior of specimens, because the change of S_u causes the change of the effective normal stress.

Fig. 8 shows the volumetric strains (ε_v) due to the application of the matric suction (S_u). As the volumetric strains are negative, the application of S_u produces the decrease of the void ratio, *i.e.*, the condensation of specimens. **Fig. 9** shows the void ratio after the application of the matric suction. The specimen consolidated with 50 kPa is looser than that consolidated with 100 kPa or 150 kPa. Then, the specimen lightly consolidated has room to contract by the application of the matric suction. This is why the specimens consolidated with 50 kPa show the large volumetric strains in **Fig. 8**.

Under the saturated condition, the magnitude of the change of the pore water pressure is equal to that of the change of the effective stress. However, this is not valid under the unsaturated condition.

The next equation for the effective stress of unsaturated soils is tentatively suggested by Bishop (1960).

$$\begin{aligned} \sigma' &= (\sigma - u_a) + \chi(u_a - u_w) \\ &= (\sigma - u_a) + \chi S_u , \end{aligned} \tag{2}$$

where χ is a parameter related to the degree of saturation and the soil type. The magnitude of parameter χ is unity for a saturated soil and zero for a dry soil. Because χ is always smaller than unity for unsaturated soils, the increase of the effective stress is always less than the magnitude of S_u in unsaturated soils.

Consequently, the influence of the application of the matric suction on the volume change behavior is not so strong as that of the applica-

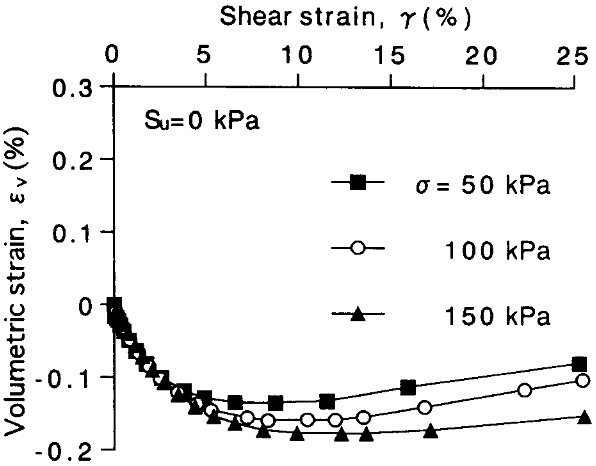

Fig. 7 Volume change characteristics of saturated Fraser River sand

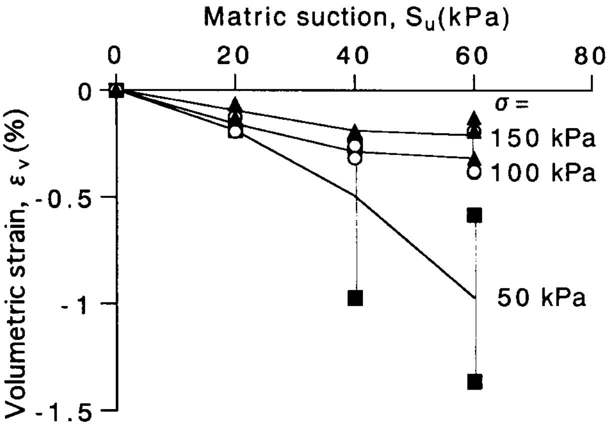

Fig. 8 Volumetric strain due to application of matric suction under different normal stress (σ)

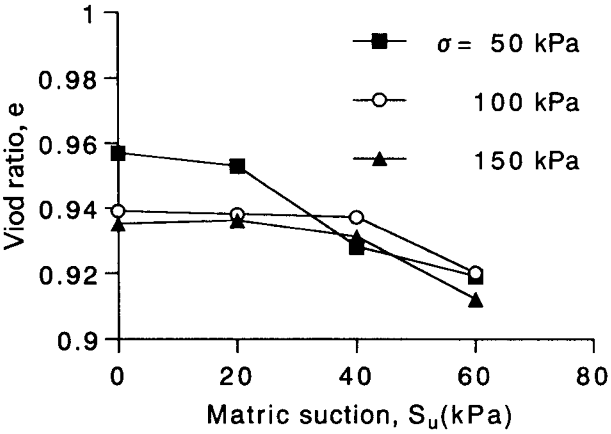

Fig. 9 Viod ratio after application of matric suction

tion of the consolidation pressure itself. Then, the volume change behavior of unsaturated specimens during shear can be different from that of saturated specimens.

Fig. 3 (b)(d)(f) show the relationships between the shear strain (γ) and the volumetric strain (ε_v) under the different normal stress (σ). Each figure shows that the degree of dilation during shear increases with the increase of the matric suction. The same result is also reported by de Campos & Carillo (1995).

Even though the influence of the matric suction on the volume change behavior is weak, 1. the specimens contract by the application of the matric suction (**Figs. 8, 9**), and, 2. the specimens, to which the greater magnitude of the matric suction is applied, show higher dilation (**Fig. 3** (b)(d)(f)). In conclusion, the effect of the suppression of the matric suction on the volume change behavior during shear must be small. This tendency is different from that caused by the application of the consolidation pressure.

4. CONCLUSION

Suction-controlled simple shear tests were carried out for an unsaturated loose Fraser River sand. Discussed are the shear strength and volume change characteristics of the unsaturated sand with the matric suction.

The shear strengths (τ_f) of the unsaturated sand with the matric suction (S_u) are greater than those of the saturated sand. Bilinear relations can be applied to the relationship between τ_f and S_u. The increase of τ_f is, however, negligibly small in the region of S_u values greater than 20 kPa.

The application of the matric suction produces two kinds of effects on the behavior of specimens ; 1) decrease of the void ratio and 2) increase of the effective confining pressure during shear. The increase of the effective stress due to the application of S_u is always less than S_u in unsaturated soils. Consequently, the suppression effect of the matric suction on the volume change behavior during shear is small, and the degree of dilation increases with the increase of the matric suction.

ACKNOWLEDGEMENTS

The experiments discussed herein were carried out at the Department of Civil Engineering, The University of British Columbia (UBC), Vancouver, Canada. The author expresses his sincere gratitude to Professor Y.P.Vaid of UBC for his support and valuable discussion. The assistance of Messrs S.Sivathayalan and J.D.Stedman with preparing specimens and with introducing the operation of the apparatus, and of Messrs H.Schrempp, D.Smith, R.S.Jackson and J.Y.K.Wong with arranging the apparatus is gratefully acknowledged.

The research at UBC was supported by the Ministry of Education, Science, Sports and Culture, Japan.

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